Interpretation of the Low-Energy Cosmic Ray Antiproton/Proton Ratio

A. W. Labrador and R. A. Mewaldt
California Institute of Technology
Pasadena, CA 91125 USA

Abstract

We examine the solar modulation of cosmic ray protons and antiprotons, and discuss the resulting effects on the low-energy antiproton/proton ratio at 1 AU. We find that the anitiproton/proton ratio at energies >3 GeV is a useful diagnostic of cosmic ray transport in the Galaxy. However, at energies <1 GeV the expected ratio is much more uncertain because of variation in the relative modulation of protons and antiprotons and uncertainties in the interstellar spectra. As a result, it is recommended that attention be given instead to interpretation of the cosmic ray antiproton energy spectrum measured rather than to the antiproton/proton ratio.

1. Introduction

Ever since the discovery of cosmic ray antiprotons more than 15 years ago there has been considerable interest possible sources of these particles in cosmic rays. Although there have been a variety of possible sources proposed (see [1] for a review), the only cosmic ray antiprotons that must exist are "secondary" antiprotons produced by the nuclear interactions of "primary" cosmic ray protons and heavier nuclei with the interstellar medium. The resulting interstellar spectrum of secondary antiprotons can then be predicted assuming that the standard acceleration/transport models derived from heavier nuclei (e.g., the B/C ratio) also apply to cosmic ray protons. Because the threshold for antiproton production in the p+p—>3p+pbar reaction is ~6 GeV, the interstellar spectrum of secondary antiprotons is expected to peak at ~2 GeV, declining sharply at both lower and higher energies because of kinematic constraints.

Cosmic ray antiproton investigations traditionally express their results in terms of the antiproton/proton ratio. To model the expected ratio at 1 AU one must take into account the effects of solar modulation on both the primary proton spectrum and the secondary antiproton spectrum. Although all published antiproton studies to date (with the exception of the work by Golden et al. [2]) have been at energies <5 GeV/nuc, most of these studies have not taken solar modulation into account in a systematic fashion.

2. Solar Modulation Studies

To investigate the effects of solar modulation we use as a reference interstellar antiproton spectrum the calculated spectrum by Webber and Potgieter (hereinafter P&W) [3]. They show that the shape of the secondary antiproton spectrum is relatively insensitive to the slope of the interstellar proton spectrum, but that its magnitude scales approximately with the integral flux of cosmic ray protons >20 GeV. For the interstellar proton spectrum we use that from P&W. Note, however, that the effects of solar modulation are further compounded by uncertainties in the low energy proton interstellar spectrum; see Gaisser and Schaeffer [4] for alternative interstellar spectra.

The effects of solar modulation were calculated using the standard spherically symmetric approach of Fisk [5], including the effects of diffusion, convection, and adiabatic deceleration. We assume a modulation boundary at 100 AU, a solar wind speed of 400 km/sec, and a rigidity–dependent diffusion coefficient, independent of heliospheric radius. We ignore the effects of drifts, thereby obtaining a lower limit to possible solar cycle effects on the antiproton/proton ratio. The strength of the modulation is adjusted to proton spectra measured at 1 AU in a series of reference years (1979, 1980, 1987, 1990, 1992, and

1993), when antiproton observations are available. The proton spectra were modulated to coincide with IMP–8 proton flux measurements at ~200 MeV [6]. The 1990 solar modulation level was selected as representative of a deep solar maximum.

Figure 1 shows modulated proton spectra for the case of solar minimum (top, 1987), solar maximum (bottom, 1990), and intermediate levels of modulation. Note that for each interstellar proton spectrum it is possible to obtain a reasonable fit to the measured intensity levels over the solar cycle simply by varying the magnitude of the diffusion coefficient. Figure 2 shows the modulated antiproton spectra at 1 AU with energies for these same cases. Antiprotons observed at 1 AU with energies ≤1 GeV are primarily the result of adiabatic deceleration of higher energy antiprotons. As a result they vary much less over the solar cycle than do low energy protons (Fig. 1), because most of the particles originate at several GeV, where the effects of solar modulation are much less.

Figure 3 shows the resulting antiproton/proton ratio. Note that the ratio at several hundred MeV varies by approximately one order of magnitude over the solar cycle. Inspection of Figures 1 and 2 indicates that these variations in the the antiproton/proton ratio are due mainly to variations in the 1 AU proton flux rather than to variations in the antiproton flux. We therefore recommend that it may be more useful to compare low energy measurements to the expected antiproton spectrum rather than to the antiproton/proton ratio.

In addition to the effects of solar modulation, there are also additional uncertainties in the interstellar spectra. For example, the assumed interstellar spectra adopted by Gaisser and Schaeffer (hereinafter G&S) [5] differ from those of W&P. Figure 4 shows that the resulting solar cycle variations are somewhat larger than for the W&P interstellar spectra, because there are fewer low energy antiprotons in their interstellar spectrum. In addition, the overall ratio is lower.

To account for the effects of solar modulation on all of the measurements, and thereby compare them to a common reference, we have divided all measurements by the corresponding calculated ratio for their time of measurement. The results are shown in

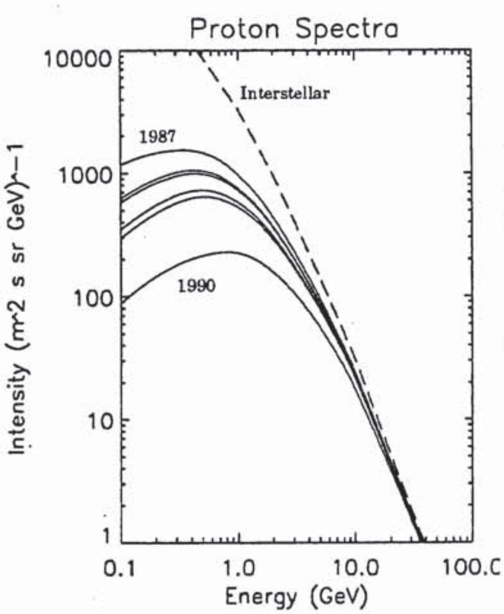

Figure 1: Interstellar proton spectrum calculated by Webber & Potgieter [3] (dashed line) and modulated (solid lines) to (from top to bottom) 1987, 1993, 1979, 1992, 1980, and 1990 levels.

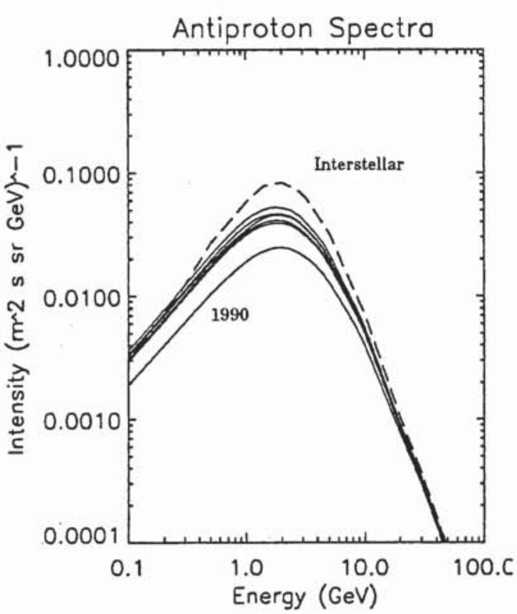

Figure 2: Interstellar antiproton spectrum calculated by Webber & Potgieter [3] (dashed line) and modulated (solid lines) to 1987, 1993, 1979, 1992, 1980, and 1990 levels (top to bottom).

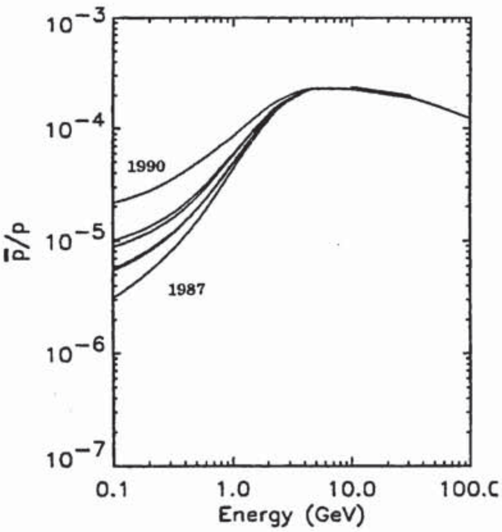

Figure 3: The calculated antiproton/proton ratios for (top to bottom) 1990, 1980, 1992, 1979, 1993, and 1987. Ratios are calculated from Webber and Potgieter [3] interstellar proton and antiproton fluxes.

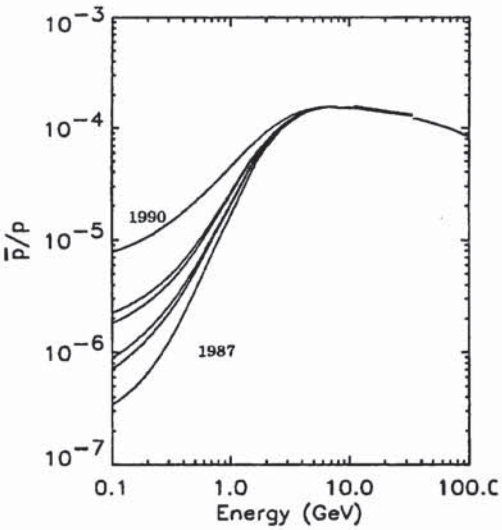

Figure 4: The calculated antiproton/proton ratios for (top to bottom) 1990, 1980, 1992, 1979, 1993, and 1987. Ratios are calculated from the median Gaisser and Schaeffer [3] interstellar proton and antiproton fluxes.

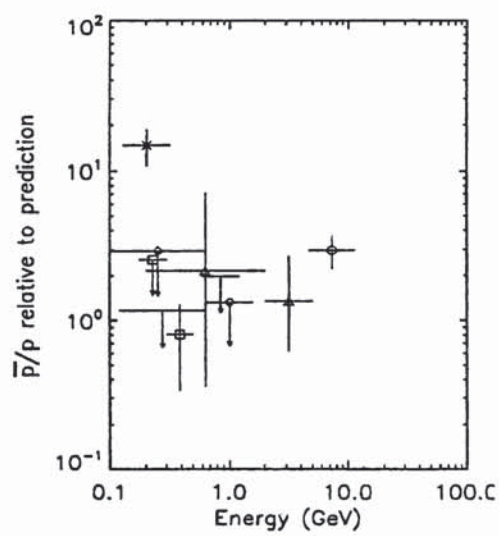

Figure 5: Measured antiproton/proton ratios divided by the calculated ratios from Figure 3. The points are Golden, et. al [2] (open circle), Bogomolov, et al. [9] (open triangles), Buffington, et al. [8] (asterisk), Stochaj [10] (no symbol), Salamon et al. [11] (open diamonds), and Yoshimura, et al. [12] (open square).

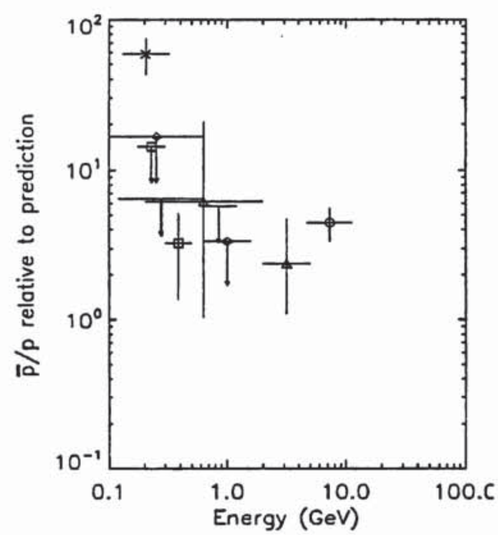

Figure 6: Measured antiproton/proton ratios divided by the calculated ratios from Figure 4. The points are Golden, et. al [2] (open circle), Bogomolov, et al. [9] (open triangles), Buffington, et al. [8] (asterisk), Stochaj [10] (no symbol), Salamon et al. [11] (open diamonds), and Yoshimura, et al. [12] (open square).

Figures 5 and 6. Note that the only two measurements that could be considered inconsistent with the models are the two very first cosmic ray antiprotons observations (Golden et al. [2], and Buffington et al. [6]) both of whom show a significant excess. However, because the median G&S spectra lead to a lower overall antiproton/proton ratio, one gets the impression of an antiproton excess from all of the finite measurements in Figure 6. It is clearly important to reconcile differences between these models.

3. Discussion

If cosmic ray antiprotons are of "secondary" origin, produced by interactions of "primary" protons with the interstellar medium, they are daughters of cosmic rays with energies > 6 GeV/nuc. Note in Figure 3 that the expected antiproton/proton ratio at energies > ~3 GeV is very insensitive to the effects of solar modulation, and it is therefore a useful diagnostic of cosmic ray transport in the Galaxy. However, at lower energies (e.g., <1 GeV), the expected antiproton/proton ratio is much more uncertain because of solar cycle variations and uncertainties in the interstellar spectra. With few exceptions, most discussions of the antiproton/proton ratio have not taken these uncertainties into account. With a number of improved antiproton measurements expected in the near future from experiments like IMAX [13], BESS [14], and MASS2 [15], it will be important to take these effects into account in their interpretation.

Acknowledgements

This work was funded by NASA under NAGW-1919. One of us (AL) is grateful for a NASA Graduate Fellowship. We thank W.R. Webber, T. Gaisser, R. Shaeffer, and R. Streitmatter for useful discussions.

References:

[1] Stephens, S.A., and Golden, R.L., Space Sci. Rev. **46**, 31 (1987).

[2] Golden, R.L., et al. Astrophysical Letters, **24**, 75 (1984).

[3] Webber, W.R., and Potgieter, M.S., Ap. J., **344**, 779 (1989).

[5] Gaisser, T.K., and Schaeffer, R.K., Ap. J., **394**, 174 (1992).

[6] Fisk, L.A. Journal of Geophysical Research, **76**, 221 (1971).

[7] McGuire, W., Schuster, P., and McDonald, F. Private communication.

[8] Buffington, A., Schindler, S.M., and Pennypacker, C.R. Ap. J., **248**, 1179 (1981).

[9] Bogomolov, E.A., et al. Proc. 20th ICRC, Moscow, **2**, 72 (1987). Bogomolov, E. A., et al. Proc. 21st ICRC, Adelaide, **3**, 288 (1990).

[10] Stochaj, S.J., Ph.D. Thesis of U. of Maryland, (1990). Also Moats, A. et al., Proc. 21st ICRC Adelaide. **3**, 284 (1990).

[11] Salamon, M.H., et al. Ap. J., **349**, 78 (1990).

[12] Yoshimura, K., et al. KEK Preprint 94-202. Submitted to Phys. Rev. Letters, March 1995.

[13] Mitchell et al. and Labrador et al., these proceedings.

[14] The BESS Team, these proceedings.

[15] The MASS2 Team, these proceedings.